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THE METHODOLOGY OF ACQUISITION AND STATISTICAL ANALYSIS OF DATA FROM THE PROCESS OF DRYING THIN WOODEN ELEMENTS

This paper presents an original methodology of acquisition and statistical analysis of data from the process of drying thin wooden items, without interference in the manufacturing schedule or process. The research was aimed at reducing the duration of the lamella drying process in a convectional drying chamber, and minimising non-conformities of dry lamellas. The authors discuss the effective application of convectional drying methods, taking into consideration non-homogeneous wood quality resulting from over- or under-drying caused by uneven or insufficient exposure to the drying agent, long duration of the drying process serving to minimise the internal stress of the material, poor efficiency of the drying process, and relatively high operational costs. Based on the tests performed, a quick drying programme is recommended. To reduce the fraction of non-conforming lamellas, the authors suggest that the arrangement of lamellas in the cage be changed so that all lamellas are protected against unconstrained deformation.

Keywords: thin wood element production, drying process, data acquisition, non--conformities, statistical inference

Introduction

The increasing rate of change in customers' requirements and expectations puts pressure on manufacturers to reduce the time spent on designing processes, mastering technologies, and starting up and optimising production [Selech et al. 2014; Gangala et al. 2017; Trojanowska et al. 2018]. Therefore, the importance of the acquisition of reliable data for analyses, aimed at obtaining insight into manufacturing processes and improving them, cannot be overestimated [Patalas--Maliszewska and Kłos 2017].

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Tool-supported data analysis finds various applications in the optimisation and management of manufacturing processes [Starzyńska and Hamrol 2013; Więcek-Janka et al. 2015], such as the detection of failures, identification of their causes, and ensuring the robustness of processes to their consequences. Results of data analyses can support the selection of optimal process settings against specified criteria. One of the methods used to support manufacturing processes is Design of Experiments (DoE): an experiment planning and performance technique [Sika and Rogalewicz 2017; Rogalewicz et al. 2018]. In a sequence of experiments designed to be performed with changing parameters, the DoE technology makes it possible to identify the parameters which have the most significant impact on the result of the process, and determine the impact value. This manner of experimenting (referred to as "active") facilitates the examination of mutual relations between process parameters.

Implementation of the DoE technology may be impeded by a lack of clear guidelines for a specific industrial application. It may be difficult to put the concept into practice where no data on the modelled process are available or where the process is affected by multiple factors. Such is the case in the wood industry, characterised by relatively complex processes and high manufacturing costs generated by variability of the input material [Kujawińska et al. 2017]. The literature shows that many practitioners take the so-called passive experimental approach, that is to say, they use data from historical records of the process rather than from specifically designed experiments, with the assumption that individual realisations of the process can be referred to levels of analysed factors, since the analysis is performed in compliance with the DoE methodology [Sedlar and Pervan 2010; Rogalewicz et al. 2018].

When even this approach is economically or technically inviable, it is recommended to adjust the number and type of experiments to external constraints and apply traditional statistical inference. The problem applies to wood manufacturing processes, including the manufacture of the top layer of a floorboard, the lamella. The lamella is an important element of the floorboard. Both the aesthetic values of the finished product and the durability of the flooring depend on its quality. Due to high material costs, active experiments on this process are not economically viable. According to a previous study [Orłowski and Walichnowski 2013], the cost of raw wood accounts for the greatest share (more than 80%) in the total cost of manufacture of the oak top layer of multi-ply engineered flooring. For comparison, the cost of tools accounts for 6% of the total in the case of a gater and 5% in the case of a band saw. Passive experiments on the manufacturing process are limited by the amount and type of data. Traditional statistical inference seems to be the right analytical tool for this type of process. It is important, however, to plan the study taking into consideration the technical and organisational constraints of the process (including the need to avoid stoppage of production) and the factors viable for analysis.

This paper presents a methodology of data acquisition from the process of drying thin wooden elements, without interference in the manufacturing schedule.

Drying of lamellas

The lamella is the top layer of a three-ply engineered floorboard (Fig. 1), made of a European or exotic species of timber of high hardness, such as oak or beech.

The technological process of manufacturing the surface layer begins with the cutting of logs into planks. Planks are cut into wet, unpolished sheets (lamellas), to be dried, polished and adjusted in length and width in subsequent operations. A finished lamella is bonded with the middle and lower layers of the block.

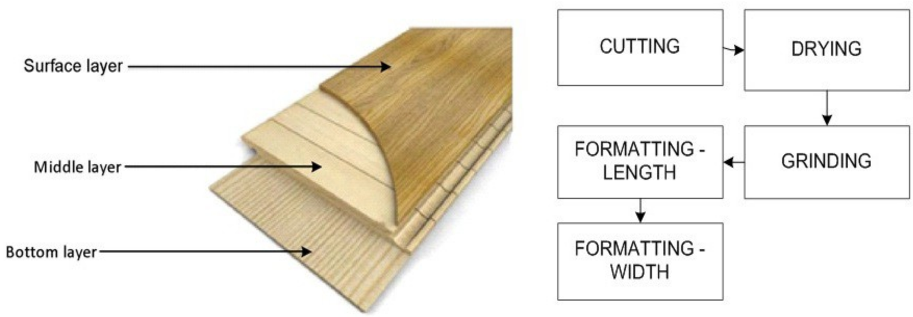


Fig. 1. Three-ply floorboard

The drying operation is of critical importance. It usually improves the properties of wood, such as dimensional stability, compatibility with coatings or glues, and mechanical properties. Removal of excess water reduces the wood's weight, and in consequence the costs of shipment and handling. Moreover, drying enhances the acoustic properties and electrical conductivity of wood, and reduces its biodegradability [Gu et al. 2013]. The drying operation accounts for 40–70% of total energy consumption in the manufacture of a wooden product [Zhang and Liu 2006].

The key to effective drying is proper supervision of the process. Drying without supervision increases the number of non-conforming lamellas, affects their utility and increases the costs of manufacture. Improper drying may cause cracking of the lamella on the surface or edges, colour change or deformation, and may therefore affect the quality of the finished product and increase the costs of waste [Cai and Hayashi 2007; Gu et al. 2013].

There are several basic drying methods, distinguished by the way in which energy is transmitted into the wood [Zhang and Liu 2006]:

- convectional – heat is transmitted by particles of gas or liquid in constant motion, which transport the energy between heat sources and the drying item, mix with the particles of expelled moisture, and carry them outwards; the convectional drying process is typically carried out in (air or steam) drying facilities or in the open air;
- contact – this method may be implemented in combination with the convectional drying process; heat is transmitted to the wood through contact with the heating surface;
- radiation – based on the transmission of energy through radiation; may be utilised in drying facilities equipped with infra-red tube lamps;
- hybrid – combinations of the drying methods described above.

Typically, parameters such as temperature, relative humidity and air circulation are monitored in the drying process. Their values depend on, among other things, the type of wood, the thickness of the drying element and requirements concerning the finished product, and affect the cost-effectiveness of the drying operation. The cost of the drying operation largely depends on its duration. Quick drying is cost-effective, but poses the risk of non-conformity of the material surface (e.g. deformation, protrusion, cracking). Slow drying may be economically inviable, as it compromises process efficiency and increases the risk of staining of the wood surface due to mould. Therefore, not only scientists, but first and foremost wood manufacturers are looking for effective ways to accelerate wood drying processes and minimise non-conformities.

Efficient implementation of the convectional drying methods analysed in this paper poses many challenges, such as the non-homogeneity of wood quality resulting from over- or under-drying caused by uneven or insufficient exposure to the drying agent, long duration of the drying operation serving to eliminate the risk of high stress of the material, poor efficiency of the process and relatively high operational costs. Practical ways to overcome these limitations are sought through empirical studies.

Research methodology

The authors undertook research to reduce the time of drying of lamellas in an industrial convection chamber and minimise the number of non-conforming lamellas.

Improvement of the drying process in the manufacturing environment is impeded by the fact that the drying facility cannot be excluded from the manufacturing schedule without stopping the manufacturing process. In such circumstances, active experiments are not possible. Another obstacle lies in the lack of sufficient data on the input material for the drying process, which would be necessary to conduct passive experiments.

In view of the above, the authors developed a research methodology which organises the marking and selection of study samples and data acquisition (without interference in the manufacturing process or schedule) in such a way that analysis of the data facilitates reliable statistical inference. The conclusions inferred may be utilised for improvement of the analysed drying process.

Further in the paper, the authors present a methodology of acquisition and statistical analysis of data from the process of drying lamellas in an industrial convection chamber. It consists of the following steps:

1. Preparation of the study:
   a. Selection of place, time and manner of carrying out the study (chamber size, cage size).
   b. Determination of organisational factors and their levels which may have an impact on the quality of the drying process (e.g. the location of cages in the chamber and the arrangement of lamellas in the cage).
   c. Selection of the input material (type and geometry of wood).
   d. Selection of the sample size.
2. Identification of the features of lamellas which may give rise to non-conformities in the drying process.
3. Definition of possible types of non-conformity of lamellas after the drying operation.
4. Selection of the sample size, in compliance with the assumptions set out in step 1.
5. Assessment of the study sample before the drying operation, in compliance with the guidelines set out in step 2, and assignment of lamellas to groups having the same features.
6. Carrying out of the drying operation, taking into consideration the factors identified in step 1b.
7. Assessment of dry, unpolished lamellas against the criteria set out in step 3.
8. Data analysis aimed at identifying the non-conforming fractions as defined in step 3, taking into consideration the organisational factors identified in step 1b.
9. Repetition of the drying operation with altered drying parameters.
10. Statistical analysis aimed at comparing non-conforming fractions from three drying processes against the determined factors – determination of statistically relevant factors and their values enabling the minimisation of non-conforming fractions.

Results and discussion

The case study was conducted at the facility of Barlinek Inwestycje Sp. z o.o., a floorboard manufacturer, as part of the BIOSTRATEG project [Biostrateg 2016]. The process of drying lamellas was examined in accordance with the methodology.

Steps 1 and 2: Preparation of the study; Identification of the features of lamellas which may give rise to non-conformities in the drying process.

The experiment was performed in a Mühlböck Type 606/1306 convection chamber, referred to within the company as VAN-28. The manufacturer provides the following specification for the chamber: heating power 280 kW, water temperature 115°C, water flow 12.5 m^3/h. The chamber is equipped with four 3 kW fans.

The internal dimensions of the loading space of VAN-28 (width × depth × height) are 6.5 × 5.3 × 4.2 m. The chamber capacity is 24 cages, 16 large and 8 small, with the following dimensions: **large cage** 2720 × 1280 × 1480 mm, **small cage** 2720 × 1280 × 983 mm.

The arrangement of cages in the chamber is presented in Figure 2.

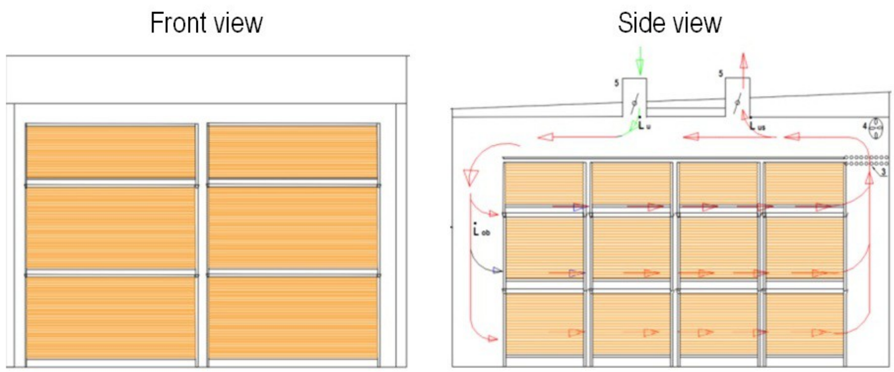


Fig. 2. VAN-28 chamber (based on data supplied by Barlinek Sp. z o.o.)

The organisational factors identified as possibly affecting the result of the drying operation included the arrangement of cages in the chamber, the arrangement of lamellas in a cage, and the class of wood [Biostrateg 2016].

The input material for the experiment was unpolished oak lamellas of rated dimensions 4.15 × 220 × 2500 mm, both knotless and knotted. It was assumed that owing to the reversion of ventilation, the right-hand and left-hand sides of the chamber had comparable drying properties. Therefore, cages with knotless lamellas were loaded into the left-hand side of the chamber, and cages with knotted lamellas into the right-hand side (Fig. 3). Such an arrangement of lamellas was important for efficient logistics in the organisation and preparation of the experiment and analysis of the results.

The experiment involved the assessment of lamellas from 10 out of 24 cages in the drying facility. In Figure 3, the cages containing the analysed lamellas are marked in purple. Knotless lamellas are contained in cages 1-5, and knotted lamellas in cages 6-10. Details concerning the input material are given in Table 1.

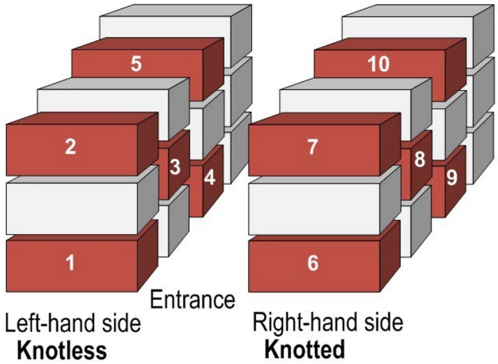


Fig. 3. Arrangement of cages for the experiment in the VAN-28 chamber (diagram by the authors)

Table 1. Detailed characteristics of the input material

No.	Dimensions			Quantity	Class of wood	Moisture content (%)
	Thickness (mm)	Width (mm)	Length (mm)			
1.	4.15 ±0.2	220 +5/-1	2450 ±20	8 large cages and 4 small cages	Knotless	~50-80
2.	4.15 ±0.2	220 +5/-1	2450 ±20	8 large cages and 4 small cages	Knotted	~50-80

A set of 600 wet lamellas with specified features was prepared for each experiment. The features of a wet lamella which might cause non-conformity after the drying operation included knots, cracks, and knotty fibre pattern [Biostrateg 2016]. Small cages (983 × 1280 × 2720 mm) held ca. 200 lamellas, and large cages (1480 × 1280 × 2720 mm) held ca. 290. Three zones, upper, middle and lower, were distinguished in each cage.

Each zone consisted of four layers, each of five lamellas with a particular material feature. The material features of lamellas were assessed during the cutting of planks. Four groups of lamellas were distinguished – those with knots, those with cracks, those with a knotted fibre pattern, and plain, i.e., without any deficiencies (Table 1).

Step 3: Definition of possible types of non-conformity of lamellas after the drying operation.

In the next step of the methodology, types of non-conformities which might occur during the drying operation were defined: cracking of the end, cracking of a knot, hump (bump), knot hole (a fallen-out knot), cracking of the surface, banana, and propeller (Fig. 4) [Biostrateg 2016].

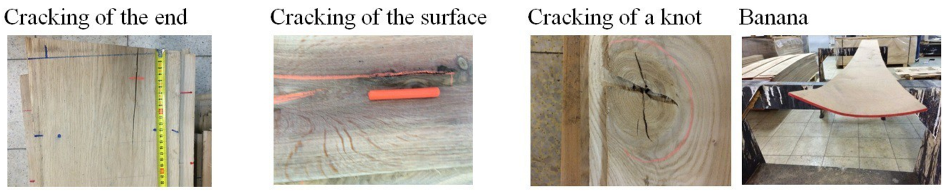


Fig. 4. Example non-conformities after the drying operation (authors' own work)

Step 4: Selection of the sample size.

The sample size was determined by the loading capacity of the drying chamber. Sixty lamellas were examined in each cage, having previously been arranged in specific zones and layers (Table 2). Six hundred lamellas were assessed in each experiment.

Table 2. Numbers of lamellas with particular features per experiment

Material feature	Number of lamellas in one layer	Number of lamellas in one cage	Number of lamellas assessed after one drying operation
Knot	5	15	150
Crack	5	15	150
Knotty fibre pattern	5	15	150
Mixed and plain	5	15	150
	TOTAL		600

Step 5: Assessment of the study sample before the drying operation, in compliance with the guidelines set out in step 2, and assignment of lamellas to groups having the same features.

Step 6: Carrying out of the drying operation, taking into consideration the factors identified in step 1.

With the support of the expertise and experience of Barlinek engineers, three drying programmes were defined. Drying was performed semi-automatically to control the values of selected parameters at specified stages of the process.

During the process, the content of moisture in the wood, M (%), was measured by means of sensors placed at selected locations in the drying chamber. The data collected from the sensors was used to control the values of process parameters 1-3. It was assumed that the duration of cooling (parameter 4) would be determined depending on the duration of drying, while the direction of the fans (parameter 5) would be reversed every two hours for each drying programme. The values of parameters for individual drying programmes at specified moisture levels are presented in Tables 3 and 4.

Table 3. Values of parameters for each of the three drying programmes

Programme 1				
M (%)	100	30	20	15
t (°C)	28	28	35	50
dt (°C)	4	5.9	8.5	11.7
UGL	12	11	9	7.8
Programme 2				
M (%)	100	30	20	15
t (°C)	28	28	34	39
dt (°C)	4.4	5.1	7.8	10.2
UGL	13	12	9.5	8
Programme 3				
M (%)	100	30	20	15
t (°C)	28	28	32	37
dt (°C)	3.1	3.7	6.6	9.4
UGL	15	14	10.5	8.5

Table 4. Comparison of the three drying programmes

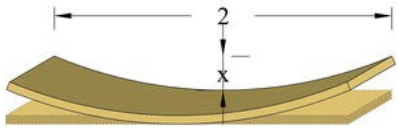
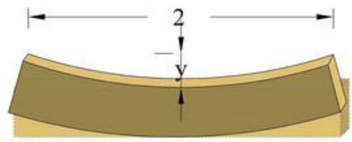
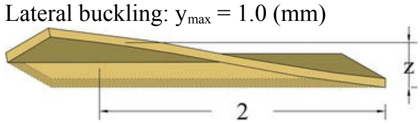
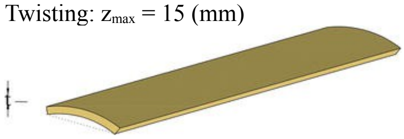
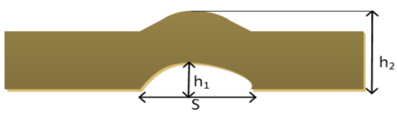
Programme	No. of cages	Duration (h)	Notes on the drying programme
1	24	67	Applied to date
2	24	73	Less severe
3	24	121	–

Step 7: Assessment of dry, unpolished lamellas against the criteria set out in step 3.

After the drying operation, the lamellas were assessed by the company's quality control officers against the acceptance criteria presented in Table 5.

Steps 8, 9 and 10: Data analysis aimed at identifying the non-conforming fractions as defined in step 3, taking into consideration the organisational factors identified in step 1b; Repetition of the drying operation with altered drying parameters; Statistical analysis aimed at comparing non-conforming fractions from three drying processes against the determined factors.

Table 5. Lamella assessment criteria

Feature	Acceptance criteria
THICKNESS	The thickness criteria are derived from the requirements for certain types of lamellas. A lamella of thickness 4.15 ±0.2 mm will be used in the experiments in Task 2 and 3. Lamellas with dimensions outside the tolerances will be marked as non-conforming.
MOISTURE CONTENT	The expected content of moisture of an unpolished lamella after drying is 12%.
GEOMETRIC DEFORMATIONS: – lengthwise curvature	 Lengthwise curvature: x_{max} = 15 (mm)
– lateral buckling	 Lateral buckling: y_{max} = 1.0 (mm)
– twisting ("propeller")	 Twisting: z_{max} = 15 (mm)
– transverse curvature	 Transverse curvature: t_{max} = 2 x thickness of the lamella
LOCAL GEOMETRIC DEFORMATIONS: HUMP	
CRACKING: – of the surface:	For knotless lamellas: frontal cracking of the lamella is unacceptable. Knotted lamellas: cracking of a knot hole, or of a knot, of maximum length 50 mm and width 3 mm, one-sided, or length 2 × 25 mm and width 3 mm, two-sided; total length of cracking on a lamella up to 600 mm, total width 3-8 mm, distributed
– at the end:	For class A: frontal cracking of the lamella is unacceptable For classes B-F: max. 2 cracks on each end (dimensions as specified for cracks on the surface)

Due to the cost of the material, it was impossible to perform a traditional active experiment on the process of drying the surface layer of a floorboard. At the same time, there were insufficient relevant data collected to perform a passive experiment. Following the steps of the described methodology, the authors ensured that appropriate technical and organisational conditions were in place to analyse the data by statistical inference.

The Chi-Square test was used for several proportions to compare the fractions of non-conformities analysed after the drying operation, taking into consideration the previously specified factors: the **class of wood** (knotless, knotted), the **drying programme** (1, 2, 3), the **arrangement of lamellas in a cage** (upper, middle and lower zone), and the **location of cages in the chamber** (front, middle section, back). The non-conformities analysed included humps, cracking of the surface, cracking of knots, knot holes, bananas and propellers. The total fraction of non-conformities was also considered for particular factor levels.

An analysis of the relevance of individual factors is presented further in the paper. The relevance was assessed on the basis of fractions of non-conformities occurring at specific factor levels. A factor was deemed relevant if, for an analysed non-conformity/non-conformities, the fraction was statistically significantly different at any of the factor levels.

Class of wood

The class of wood proved to be irrelevant for each of the analysed drying programmes (level $p > 0.05$). No statistically significant differences occurred between the fractions of non-conforming lamellas in the knotted and knotless classes (Table 6).

Table 6. Test statistics

Class of wood	Programme 1	Programme 2	Programme 3	Class of wood	Total fraction of non-conforming lamellas for three drying programmes
Knotless	88,00%	87.7%	100%	Knotless	91.7%
Knotted	93,00%	99.3%	98,00%	Knotted	96.7%
N	543	561	594	N	1796
df	1	1	1	df	
chi-sq.	0.414	2.183	0.061	chi-sq.	11.87
p	0.520	0.139	0.806	p	0.001

However, the total fraction of non-conforming lamellas in the knotless class was significantly lower than in the knotted class ($p < 0.001$) (Table 6). This may follow from the fact that knots, knotted fibre patterns and cracks naturally occur less frequently in the knotless classes of wood (classes A and B), which translates directly into a smaller number of defects occurring in the drying process.

Drying programme

A comparison of the three drying programmes shows that on average, the best result was achieved for Programme 1: ca. 90% of lamellas were non-conforming in the analysed sample of 600 lamellas. The corresponding values were ca. 94% and 99% for Programmes 2 and 3 respectively. The differences are statistically insignificant ($p = 0.309$) and may be caused by the random selection of the sample. Therefore, the initial conclusion may be drawn that the drying programme has no impact on the occurrence of defects (Table 7).

Table 7. Test statistics

Class of wood	Total fraction of non-conformities for three drying programmes	Cracking of the end	Cracking of the surface	Knot hole
Programme 1	90,00%	59.8%	4.7%	12.3%
Programme 2	93.5%	67.7%	7.2%	16.3%
Programme 3	98.8%	70.8%	15.5%	20.2%
N	1696	1190	164	293
df	2	2	2	2
chi-sq.	2.350	5.820	42.378	11.311
p	0.309	0.054	<0.0001	0.003

An analysis of the fractions of particular non-conformities occurring in lamellas in various drying programmes shows that the drying programme is relevant for cracking of the end of the lamella ($p=0.054$), cracking of the surface ($p < 0.0001$), and knot holes ($p = 0.003$) (Table 7). A significantly lower level of non-conformity was observed for Programme 1, the shortest of the three drying programmes.

Considering that the input material was of the same quality for the entire study (there were no significant differences implying that some batches of the material might be of better or worse quality when leaving the lumber mill), the above results seem to confirm the conclusion that the drying programme, or more specifically the duration of the drying operation, does not have any material impact on the fraction of non-conforming lamellas.

Arrangement of lamellas in a cage

The results of an analysis of non-conformities by the arrangement of lamellas in the cage are similar to the results by drying programme (Table 8). The only exception was observed for humps, which occur mainly in the upper zone of the cage (35% on average) and only occasionally in the lower zone (8% on average). For each drying programme, the fraction of non-conformities of the hump (bump) type is higher in the upper zone of the cage, and the difference is statistically significant ($p < 0.0001$ for all three drying programmes). This may be caused by the fact that lamellas in the lower parts of the cage are pressed by the layers above them, and cannot freely change their shape. Lamellas in the top layer, on the other hand, are prone to deformations caused by variable stresses occurring in the drying process.

Location of the cage in the chamber

The results of an analysis of the location of the cage in the chamber failed to show any statistically significant differences between the fractions of non--conforming lamellas. This means that the distributions of non-conformities in the parts of the chamber – at the front, in the middle and at the back – are comparable.

Conclusions

The tests conducted here show that Programme 1, the shortest of the three drying programmes, may be used for drying lamellas. Longer and slower drying fails to reduce significantly the number of non-conforming lamellas. The three drying programmes produce comparable results.

However, the arrangement of lamellas in the cage should be re-designed to protect all lamellas from deformation. In this way, the number of lamellas with humps – a non-conformity of critical importance in the next operation, namely grinding (it poses a risk of inaccurate grinding) – could be reduced. In the authors' opinion, minimisation of the number of non-conforming lamellas after the drying operation would require the design and implementation of a new technology for drying thin items (3-6 mm) or lamellas. The VAN-28 type of drying equipment, used for drying lamellas, is designed for drying wood planks. The fact that thin lamellas are dried in equipment designed for drying elements thicker than 25 mm may be the reason for the high unpredictability of the process.

The diverse physical, chemical, mechanical, biochemical, and other properties of wet wood, and quality requirements concerning the dry product, have driven the development of various drying technologies and equipment. It is difficult to define a universal drying method or an optimal technical solution for

Table 8. Test statistics

Zone in the cage	Cracking of the end (%)			Bump (hump) (%)			Cracking of the surface (%)			Cracking of a knot (%)			Knot hole (%)			Banana/propeller (%)		
	Drying programme																	
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Upper	63.5	68	73	41.0	34.0	42	3.5	8.5	18	51.5	53	46	12.5	20	22	2.0	4.5	0
Middle	58.0	71	71	17.5	12.5	11	5.5	4.5	14	60.0	55	53	10.0	16.5	19	2.0	0	1
Lower	58.0	64	68	7.5	9	9	5.0	8.5	14	55.5	48	55	12.5	12.5	20	1.0	1.0	0
N	359	406	424	132	111	124	28	43	92	333	312	308	70	98	122	10	11	2
df	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
chi-sq.	0.67	0.73	0.36	53.77	39.62	66.25	0.93	2.98	1.39	1.32	1	1.74	0.71	3.45	0.46	0.8	12.18	4
p	0.71	0.7	0.84	<0.0001	<0.0001	<0.0001	0.63	0.23	0.5	0.52	0.61	0.42	0.7	0.18	0.8	0.67	0.002	0.14

a drying facility which would meet certain requirements. Therefore, there is a need for empirical experimental studies to select the method and parameters of the drying process appropriate for specific materials, as well as requirements concerning quality and efficiency.

The original study method presented in this paper takes into consideration technical, organisational and financial constraints, that is, the manufacturing environment (often ignored in scientific papers in this field of study). Contrary to the traditional approach to planning experiments (compliant with the DoE methodology and passive experiments), the organisation of the drying process presented in this paper makes it possible to collect data which may be used for analyses and statistical inference.

The original method presented in this paper is universal and applicable to other types of research, not only in the wood industry.

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